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by John B. McDevitt

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SUMMARY

An experimental study has been made of a method for extending the useful operating range of low-density hypersonic wind tunnels. A gas injection scheme is utilized for increasing the stream momentum in the test-section boundary layer in order to eliminate upstream feedback of pressure disturbances in the thick viscous layer at the tunnel walls. Test results obtained in a helium tunnel at Mach numbers from 10 to 25 indicate that energizing the test-section boundary layer is an effective means for avoiding the feedback problem and is particularly useful as a means for starting and maintaining steady hypersonic flow in the test section when models creating large asymmetrical flow disturbances are being tested. The minimum tunnel compression ratio required for the design Mach number is also significantly reduced when an injector system is used since the energy of the injected medium contributes to the energy of the stream entering the diffuser. A stream energy parameter, independent of the test Mach number, was found to be useful in correlating the test data relating to the required operating conditions for maintaining stable hypersonic flow in the test section.

INTRODUCTION

A characteristic feature of hypersonic flows is the strong effect of fluid viscosity in producing very thick boundary layers on surfaces immersed in the flow. In the hypersonic, low-density wind tunnel the presence of a thick boundary layer at the tunnel walls is particularly troublesome as downstream pressure disturbances may feed back through the boundary layer and adversely affect the flow in the tunnel nozzle.

Considerable knowledge of the performance of hypersonic nozzles has been acquired in recent years, particularly in regard to the operation of hypersonic helium tunnels. For example, at the Ames Research Center experience with helium tunnels indicates that the presence of the tunnel-wall viscous layer does not noticeably affect normal aerodynamic testing procedures at free-stream Mach numbers of about 10 for tunnel driving pressures as low as 200 psia. At test Mach numbers of about 20, it was found that a feedback problem could arise in the force testing of asymmetric configurations if the tunnel were operated at driving pressures of less than about 1500 psia. However, when higher pressures, greater than about 2000 psia, were used it was found that consistent and reliable test data could be obtained.

As the test Mach number is increased above 20, the wall viscous effects become increasingly troublesome. Hypersonic viscous effects in a helium tunnel at test Mach numbers of about 30 are discussed in reference 1. In this case, it was found that the tunnel flow was influenced by the model shape and size to the extent that impact probes with the same shape as the models to be studied were required for calibrating the tunnel.

The experience with hypersonic helium tunnels may be summarized, at least in a qualitative manner, as follows: At test Mach numbers of about 10, the wall viscous-layer feedback problem is not present to a noticeable degree; at Mach numbers of about 20, the feedback problem can usually be eliminated by operating the tunnel at sufficiently large supply pressures; and at Mach numbers of about 30, a direct coupling between the test model flow field and the wall viscous layer exists such that special flow-calibration techniques must be used for each model studied.

A method for eliminating the feedback problem, and thereby extending the useful operating range of hypersonic nozzles, is described in this report. A gas-injector system is used to increase the level of the stream momentum in the test-section boundary layer, but without disturbing the high-speed, inviscid core of the test section. In this concept the momentum of the injected gas is intended to serve as an effective barrier to prevent upstream feedback of pressure disturbances near the tunnel walls. The usefulness of this concept was investigated in the Ames 14-inch helium tunnel and the results of this investigation are presented in this report.

NOTATION

Primary Symbols

A cross-sectional area, sq in.

A^* cross-sectional area of sonic throat, sq in.

E correlation parameter (see eq. (6) or (7)), lb/sq in.

k numerical constant in equations (1) or (2)

$\dot{m}$ rate of mass flow, slugs/sec

M Mach number

p_{t_1} total pressure (stagnation pressure if the gas were brought to rest isentropically), psia

p_{t_2} stagnation pressure behind normal shock (pitot pressure), psia

p_1 static pressure, psia

$\overline{p}_{sp}$ — pressure in downstream low-pressure storage spheres when hypersonic flow in the tunnel test section breaks down, psia

q — dynamic pressure, psia

t^* — sonic throat opening for the annular injector (see fig. 10), in.

T_t — total temperature, $^{\circ}R$

z — vertical displacement from tunnel center line, in.

α — angle of attack, deg

Subscripts

i — condition corresponding to isentropic channel flow

N — nominal value

∞ — free-stream condition

$(\ )_{exit}$ — properties of injected gas at the downstream exit of the injector system

APPARATUS AND TESTS

The Ames 14-inch helium tunnel, shown schematically in figure 1, was used in the present experimental study. This facility is of the blowdown type and uses a common contoured nozzle with interchangeable throat sections to provide nominal test-section Mach numbers of 10, 17, 21, and 25. Typical pitot-pressure surveys in the test section are shown in figure 2. The tunnel discharges into several large spheres which are evacuated to about 0.2 psia prior to each test run. Test run times of 2 minutes or more are available for each of the nominal Mach numbers.

The experimental study was conducted in two parts. For the first part, which was quite preliminary, the injector system consisted of a series of small nozzles installed around the inside periphery of the primary nozzle near the upstream edge of the test section. For the second part the tunnel test section was removed and replaced by an "open" test section having an annular injector incorporated at the upstream edge of the test section. Detailed descriptions of the geometry of the two injector systems used will be deferred to later sections of this report.

The effect of gas injection on the performance of the tunnel was determined in a qualitative manner by measuring the pressure, $\overline{p}_{sp}$, in the downstream vacuum spheres at breakdown of the hypersonic flow in the test section. A pitot rake was installed in the tunnel test section for determining the manner in which gas injection influenced the tunnel flow and for determining when breakdown of the flow occurred. The pitot pressures were measured by diaphragm-type, strain-gage pressure transducers. The impact pressures for a few representative pitot tubes across the test section were converted to digital form and displayed visually so that the behavior of the flow could be monitored during each test run.

The breakdown of the flow was easily determined in some cases but not in others. When an injector system was used in the proper manner (i.e., in the underexpanded condition), the flow in the test section was invariant with time until breakdown occurred, which appeared to be instantaneous across the test section. Without an injector system the measured impact pressures varied with run time. Changes in impact pressures in the tunnel boundary layer would be noted first, followed by changes in the central high-speed core, beginning at the outer edge and moving inward toward the tunnel center line. The deterioration of the flow was quite rapid once the high-speed core was affected, with complete breakdown of the hypersonic flow occurring within a few seconds after the flow at the tunnel center line had abruptly changed from the initial steady value. The run time when flow breakdown occurs was arbitrarily defined in cases of this nature as the time when the impact pressure at the tunnel center line was noticeably affected.

Although most of the information presented in this report was obtained from pressure measurements, a direct measure of the effectiveness of an injector system in alleviating a tunnel-wall feedback problem was made by force testing a blunt, asymmetric model for which difficulty had been encountered in the past in obtaining reliable test data at a free-stream Mach number of 21. For these tests a conventional sting-mounted model and strain-gage balance assembly were used.

RESULTS AND DISCUSSION

As mentioned previously, the present experimental study was conducted in two parts. The initial tests were made using a discrete mode of gas injection for energizing the tunnel boundary layer. The second phase of the investigation involved the use of an annular injector. The test results obtained from the two investigations will be presented separately since the test apparatus used was quite different in the two cases. The information obtained from the two studies, however, is complementary, and, as a result of both studies, certain conclusions are evident regarding the effectiveness of the present approach in extending the useful operating range of a low density, hypersonic tunnel.

Discrete Mode of Injection

The initial tests were made using the crude injector system shown in figure 3. A series of eight small nozzles were installed around the inside periphery of the tunnel at the upstream edge of the test section. These small nozzles were designed to have an exit Mach number, if underexpanded (exit static pressure greater than the local free-stream static pressure in the test section), of 12.5. As will be demonstrated subsequently, the proper use of an injector system in the present application is in the underexpanded condition and this requires that the supply pressure of the gas to the injectors, $(p_{t_1})_{injectors}$, satisfies the inequality

$$(p_{t_1})_{injectors} > \frac{(p_1/p_{t_1})_{tunnel}}{(p_1/p_{t_1})_{injectors}} (p_{t_1})_{tunnel}$$

where the quantity p_1/p_{t_1} is evaluated at the test-section Mach number for the tunnel and at the design "exit" Mach number for the injectors. For the present case, where the injector nozzles were designed for an exit Mach number of 12.5, the requirement for underexpanded flow is indicated in figure 4.

A pitot-survey rake, not shown in figure 3, was installed in the tunnel test section and used to determine the manner in which the gas injection altered the flow in the test section and to determine when breakdown of the flow occurred.

Effect of injector system on tunnel performance.- The measured pressure in the downstream vacuum spheres at breakdown of the hypersonic flow in the test section, $\overline{p}_{sp}$, is considered here to be a measure of the "performance" of the tunnel. The effect of the injector system on tunnel performance was determined for a wide range of test conditions with helium as the injection medium. A few test runs were also made with air as the injection medium. (Since it will be convenient, for the most part in the following discussion, to present normalized values of the measured performance data, the actual measured values of $\overline{p}_{sp}$ will not be discussed but these values are tabulated in table I.)

Measured values of $\overline{p}_{sp}$, normalized with respect to conditions of no mass injection, are presented in figure 5 for helium gas injection. For the tunnel nominal Mach number of 10, which is less than the design Mach number of the injection nozzles, data were obtained with the injection nozzles both overexpanded and underexpanded. In the overexpanded condition, considered here to be "off design," the effect is detrimental in that the pressure in downstream storage spheres at breakdown of the hypersonic flow in the test section was decreased. In the underexpanded condition the nozzles operate supersonically with further expansion occurring within the tunnel boundary layer. In this case the effect is beneficial. The test results for nominal Mach numbers of 17, 21, and 25, shown in figure 5, were obtained with the injection nozzles underexpanded in all cases.

Since a common injector system and test section were involved in these tests, the mass flow of the injector system, relative to that for the tunnel, varied considerably; hence, it is informative to present the results in terms of the ratio of mass flows, as is done in figure 6. The test results presented in this figure summarize the effect of the injector system on tunnel performance. It is apparent that this rather crude injection system is quite effective in raising the level of the downstream diffuser pressure at which the tunnel is able to operate. For example, with helium injection at a mass-flow rate equal to that for the tunnel, the over-all compression ratio required to maintain hypersonic flow in the test section is reduced to slightly less than one-half that for no mass injection. It should be recognized, however, that the use of this injection system does not significantly change the available running time of the tunnel since the total mass flow is increased in about the same proportion as is $\overline{p}_{sp}$.

<u>Correlation of performance data</u>.- It will be demonstrated here that a parameter proportional to the stream energy may be used to correlate test data relating to the required operating conditions for maintaining hypersonic flow in the test section. In a helium tunnel of the type considered here the thermal energy of the stream is negligibly small and the impact pressure may be used as a convenient measure of the stream energy per unit volume of flow. At hypersonic Mach numbers the following approximate relationships may be used:

<u>Air</u>

$$\left.\begin{aligned} \frac{p_{t_2}}{p_{t_1}} &= \frac{360}{M_i{}^5}, \qquad \frac{A_i}{A^*} = \frac{M_i{}^5}{216} \\ p_{t_2}A_i &= 1.67p_{t_1}A^* \end{aligned}\right\} \tag{1}$$

<u>Helium</u>

$$\left.\begin{aligned} \frac{p_{t_2}}{p_{t_1}} &= \frac{22.9}{M_i{}^3}, \qquad \frac{A_i}{A^*} = \frac{M_i{}^3}{16.0} \\ p_{t_2}A_i &= 1.43p_{t_1}A^* \end{aligned}\right\} \tag{2}$$

where A^* and A_i are the cross-sectional areas of the sonic throat and the hypersonic inviscid stream, respectively, and M_i is the hypersonic Mach number corresponding to A_i.

It is interesting to note that, for a given A^*, p_{t_1},

$$\frac{(p_{t_2}A_i)_{air}}{(p_{t_2}A_i)_{helium}} = 1.17 \tag{3}$$

which implies that the use of air as an injection medium for raising the energy level should give slightly better results than the use of helium. However, with air, the mass flow is considerably larger. The mass-flow rates are, in the two cases, Air

$$\dot{m} = (7.25\times10^{-4})p_{t_1}A^* \sqrt{\frac{520}{T_t}} \tag{4}$$

Helium

$$\dot{m} = (2.85\times10^{-4})p_{t_1}A^* \sqrt{\frac{520}{T_t}} \tag{5}$$

When an injector system is used in conjunction with the hypersonic tunnel, the stream energy of both systems is considered to be additive. A parameter proportional to the average energy per unit volume in the test-section stream is the following,

$$E = \frac{(p_{t_2}A_i)_{tunnel} + (p_{t_2}A_i)_{injectors}}{A_{test\ section}} \tag{6}$$

The quantity $p_{t_2}A_i$ may be expressed in terms of the driving pressure, p_{t_1}, and the sonic throat area, A^*, according to equations (1) and (2). Thus, an alternate expression for E is the following,

$$E = \left(kp_{t_1} \frac{A^*}{A_i} \frac{A_i}{A_{test\ section}}\right)_{tunnel} + \left(kp_{t_1} \frac{A^*}{A_i} \frac{A_i}{A_{test\ section}}\right)_{injectors} \tag{7}$$

where $k = 1.67$ for air, $k = 1.43$ for helium (see eqs. (1) and (2)). (It might be noted that the dimensional units of the energy parameter, as used here, are the same as those for the driving pressure, p_{t_1}.)

The measured pressures in the downstream low-pressure spheres at breakdown of the tunnel hypersonic flow are presented in figure 7 with E as the correlating parameter. Data are presented for no mass injection and with mass injection at the highest rates used for each of the nominal test-section Mach numbers. Within the accuracy of the test procedure the data correlate remarkably well (the offset near the origin is believed to be the result of viscous losses in the tunnel, diffuser, and piping to the vacuum spheres). Note that the Mach number does not enter as a significant parameter. This is in contrast to the usual method of presenting tunnel compression ratio as a function of Mach number as is illustrated in figure 8.

Pitot-pressure surveys.- A few pitot-pressure surveys were conducted to determine the effect of the boundary-layer gas injection on the flow characteristics in the tunnel test section. The pitot surveys indicated that the injection process did not alter the flow characteristics in the central, high-speed core in the region immediately adjacent to the exit of the small nozzles. Downstream from the exit of the small nozzles at a location equal to the tunnel diameter (about 14 in.), the mixing of the injected gas with the main tunnel stream was such as to affect the outer portion of the high-speed core as well as the tunnel boundary layer. At a downstream location equal to about two tunnel diameters, the influence of the injected gas was felt throughout the test section (a more or less complete mixing of the streams). These measurements indicated that tunnel boundary-layer injection is feasible in that the high-speed portion of the tunnel stream immediately adjacent to the injector system is not affected by the injection process and this region may be used in the normal way for aerodynamic force testing of sting-mounted models. It is recognized, however, that in aerodynamic studies of model base flows and/or wake characteristics, a problem could arise if the injected stream significantly alters the geometry of the model wake.

Effectiveness of the injector system in eliminating feedback in the tunnel boundary layer.- Some information regarding the effectiveness of the injector system in preventing feedback at the tunnel walls was obtained by measuring the forces on a blunt, asymmetric model for which difficulty had been encountered in the past in obtaining reliable test data at a Mach number of 21.

The configuration involved was a blunt half-cone with a semivertex angle of 30° (see sketch at the top of fig. 9). The measured drag coefficients for this model at angles of attack (measured with respect to the flat upper surface of the model) from -12° to $+12^{\circ}$ are presented in figure 9 for tunnel driving pressures of 1400 and 2200 psia. The data presented in the upper half of this figure were obtained without the use of the injector system. For the higher tunnel driving pressure the test data (square symbols) are believed to be reasonably accurate since they agree closely with other test data for this configuration at hypersonic speeds. At the lower tunnel driving pressure, data are presented for two test runs (circular symbols, runs 1 and 2). For test run 1 the model was at zero angle of attack during the starting of the tunnel flow, then pitched downward to -12° and data were acquired in 2° increments from -12° to $+12^{\circ}$. For test run 2 the model was initially at -12° (and hence appeared to be more or less symmetric to the oncoming flow) during the starting of the flow. The erratic behavior of the test data for these two runs is believed to be due to a coupling between the asymmetric flow field of the model and the tunnel boundary layer.

In the lower half of figure 9 data are presented for the case where the injector system was used with the same driving pressure as the tunnel (p_{t_1} = 1400 psia). (For this test the model was located immediately downstream of the injector nozzles, but in a region known from pitot surveys to be unaffected by the injected gas.) The test data obtained at the higher tunnel driving pressure (p_{t_1} = 2200 psia) are included for comparison purposes and, in this case, the differences in the test data for the runs are within the experimental accuracy of the tests. It is quite apparent that the injector system was effective in preventing the coupling between the model flow field and the tunnel boundary layer.

Annular Injection

The previous results, obtained with several small nozzles installed within the tunnel, demonstrated the feasibility of gas injection as a means for improving the performance and extending the usefulness of hypersonic facilities. A more efficient method for energizing the tunnel boundary layer might be the use of an annular injector. In order to explore this possibility the test section of the tunnel (see fig. 1) was removed and replaced by a box-like structure containing an "open" test section and the annular injector system.

The annular injector is shown schematically in figure 10. A sliding adjustment, as indicated in figure 10, permitted the injector first-throat area to be varied. The downstream portion of the annulus ("injector extension") was removable. A scoop, adjustable fore and aft, was used as the entrance to the tunnel diffuser. A pitot-survey rake and a 20° half-angle cone model were also provided, as shown in the photograph of figure 11. The cone model had a base diameter of 3 inches and could be mounted at angles of attack of 0°, $\pm 10^{\circ}$, and $\pm 20^{\circ}$. When mounted at a large angle of attack, this model induced a large asymmetric flow disturbance in the test section. Although aerodynamic forces on the cone were not measured, the pitot-survey apparatus provided a means for determining the stability of the test-section flow. Helium was used exclusively as the injected gas for the tests with the annular injector and care was taken to operate the injector system in the underexpanded condition in all cases.

Preliminary tests were made with and without the "injector extension" (see fig. 10). It was determined, at least within the accuracy of the measurements, that the presence of the injector extension did not noticeably affect the performance characteristics of this injector system. The extension was then discarded and not used in any of the test results which follow.

Although the primary intent of the present investigation was to evaluate the performance characteristics of an annular injector system, some information regarding the relative performance of open and closed test sections and the effect of a conical test model on tunnel performance were obtained. A comparison of tunnel performance for closed and open test sections is presented in figure 12 for a nominal test Mach number of 21. Since the magnitude of $\bar{p}_{sp}$ (pressure in the downstream vacuum spheres at breakdown of the hypersonic flow in the test section) is considered here to be a measure of the performance of the tunnel, it is evident from the data of figure 12 that the tunnel performance decreases considerably as the length of the free jet increases.

The presence of a conical test model has a substantial effect on the tunnel performance, at least for a test Mach number of 21, as is indicated by the data presented in figure 13. When the cone was at zero angle of attack, or removed from the test section, the tunnel could be started for tunnel driving pressures as low as 1000 psia. (When the cone model was used it was necessary, however, to place the diffuser scoop near the model as shown in the sketch at the top of fig. 13.) For the cone model at 20° angle of attack hypersonic flow in the tunnel could be established only when the highest driving pressure (p_{t_1} = 2000 psia) was used. When the injector system was used momentarily during the starting phase, it was found that flow could also be established with the cone at $\alpha = 20^{\circ}$ for a tunnel driving pressure of 1500 psia but at a driving pressure of 1000 psia the tunnel could not be "started" even with the help of the injector system.

Effect of annular injector system on tunnel performance.- The effect of the annular injector on tunnel performance for a nominal test-section Mach number of 21 is illustrated in figure 14. The sonic throat opening, t^*, for the injector was 0.005 inch and the estimated exit Mach number of the injected gas was about 13. In the left-hand side of figure 14, performance data are presented for tests conducted with the cone model at angles of attack of 0° and 20°. With the injector system operating, the effect of introducing a large asymmetric disturbance in the tunnel by pitching the cone to a large angle of attack is to reduce slightly the performance of the tunnel. Without the injector system ($\dot{m}_{injector} = 0$), the effect of model angle of attack is large.

For the tests with the cone model at zero angle of attack, the performance data, normalized with respect to conditions of no mass injection, are correlated in the right-hand side of figure 14. As in the case of the injector system for the closed test section, described earlier in this report, the effect of gas injection is to improve significantly the performance of the tunnel.

The actual measured values of $\overline{p}_{sp}$ have been correlated in figure 15 using the stream energy parameter defined by equation (6). In this figure representative data are presented for tests at nominal test-section Mach numbers of 10 and 21 with the cone model installed at $\alpha = 0^{\circ}$. The correlation curve is nearly identical with the correlation curve presented earlier (fig. 7) for the discrete injector system. However, a direct comparison of the performance of the two injector systems cannot be made since the annular injector was applied with an open test section and with a cone model, whereas the discrete injector system was used with a closed test section and without a cone model.

Pitot-pressure surveys.- Typical pitot-pressure surveys at several stations downstream from the injector are presented in figure 16 to illustrate the extent to which the injected gas has mixed with the tunnel stream. Immediately downstream of the injector the influence of the injected gas is confined to the tunnel boundary layer and the adjacent high-speed core of the tunnel, which has not been affected, may be used for aerodynamic force testing of models.

The pitot rake used in the present tests also provided some information regarding feedback in the tunnel boundary layer when the cone model was installed at angle of attack so as to induce a large asymmetric disturbance to the flow. The variations of pitot pressure at several vertical locations in the test section with run time are presented in figure 17 for a nominal test Mach number of 21, tunnel driving pressure of 1500 psia, and cone model at $\alpha = 20^{\circ}$ (see sketch at top of fig.). The open symbols represent measurements obtained without the injector system although the injector was used momentarily (immediately prior to the run and during the first few seconds) to start the tunnel flow. The solid symbols represent measurements obtained at the same test conditions but with the injector operating at a mass-flow rate equal to that for the tunnel. When the injector system was not used, the measured pitot pressure changed continually in the boundary-layer region of the tunnel, but measurable changes in the high-speed core of the tunnel did not occur until immediately prior to breakdown of the flow. With the injector system in use, no measurable change in any of the pitot measurements were noted and breakdown of the flow was instantaneous across the test section. These results indicate that the present gas-injection scheme is quite effective in isolating the main tunnel flow from downstream disturbances.

Effect of injector sonic throat geometry on performance.- The various test results presented previously in this report for the annular injector were obtained with an annular sonic throat opening, t*, (see fig. 10) of 0.005 inch. In this case the Mach number at the exit of the injector was estimated to be about 13. A sonic-throat opening of 0.0025 inch, which provides an exit Mach number of about 17, was also tried and the performance for the two cases are compared in figure 18. Within the accuracy of the measurements, essentially the same performance was obtained at equal mass-flow rates.

Since the annular opening of the sonic throat, t*, is necessarily small, and difficult to set accurately and maintain, a brief investigation was made of a sonic throat with 48 discrete holes, equally spaced azimuthally, in place of the annular slot. The performance of this injector throat was slightly inferior to that for a continuous annular sonic throat (see fig. 19).

CONCLUDING REMARKS

The present experimental study has demonstrated the feasibility of gas injection into the boundary layer of a low-density hypersonic tunnel as a means for extending the useful operating range of the tunnel. In general, the experimental tests indicated that energizing the test-section boundary layer is an effective means of avoiding upstream feedback of pressure disturbances in the thick viscous layer at the tunnel walls and is particularly useful as a means for starting and maintaining hypersonic flow in the test section when models creating large asymmetrical flow disturbances are being tested.

The required tunnel compression ratio is also significantly reduced when an injector system is used since the energy of the injected medium contributes to the energy of the stream entering the diffuser. A stream energy parameter, independent of the test Mach number, was found to be useful in correlating the test data relating to the required operating conditions for maintaining stable hypersonic flow in the test section.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., May 5, 1965

REFERENCE

1. Johnson, Robert H.: Hypersonic Viscous Effects in Wind Tunnels. ARS J., vol. 31, no. 7, July 1961, pp. 1022-1024.

TABLE I.- SUMMARY OF TEST RESULTS FOR THE DISCRETE INJECTOR SYSTEM

[See fig. 3]

M_N	Injection medium	p_{t_1}, psia		$\bar{p}_{sp}$, psia	$\frac{A^*_{injectors}}{A^*_{tunnel}}$	$\frac{\dot{m}_{injectors}}{\dot{m}_{tunnel}}$
		Tunnel	Injectors			
10	Helium	100	0	0.85	0.03	0
			100	.79		.03
			200	.81		.06
			400	.91		.12
			800	1.16		.24
		300	0	2.76		0
		300	1000	3.13		.10
17		1000	0	2.00	.14	0
			500	2.14		.07
			1000	2.39		.14
21		2000	0	1.15	.42	0
			500	1.33		.11
			1000	1.43		.21
			1500	1.62		.32
			2000	1.72		.42
25		2500	0	.41	1.25	0
			500	.56		.25
			1000	.66		.50
			1500	.81		.75
			2000	.98		1.00
21	Air	2000	500	1.35	.42	.28
			1000	1.50		.54
			1900	1.77		1.02

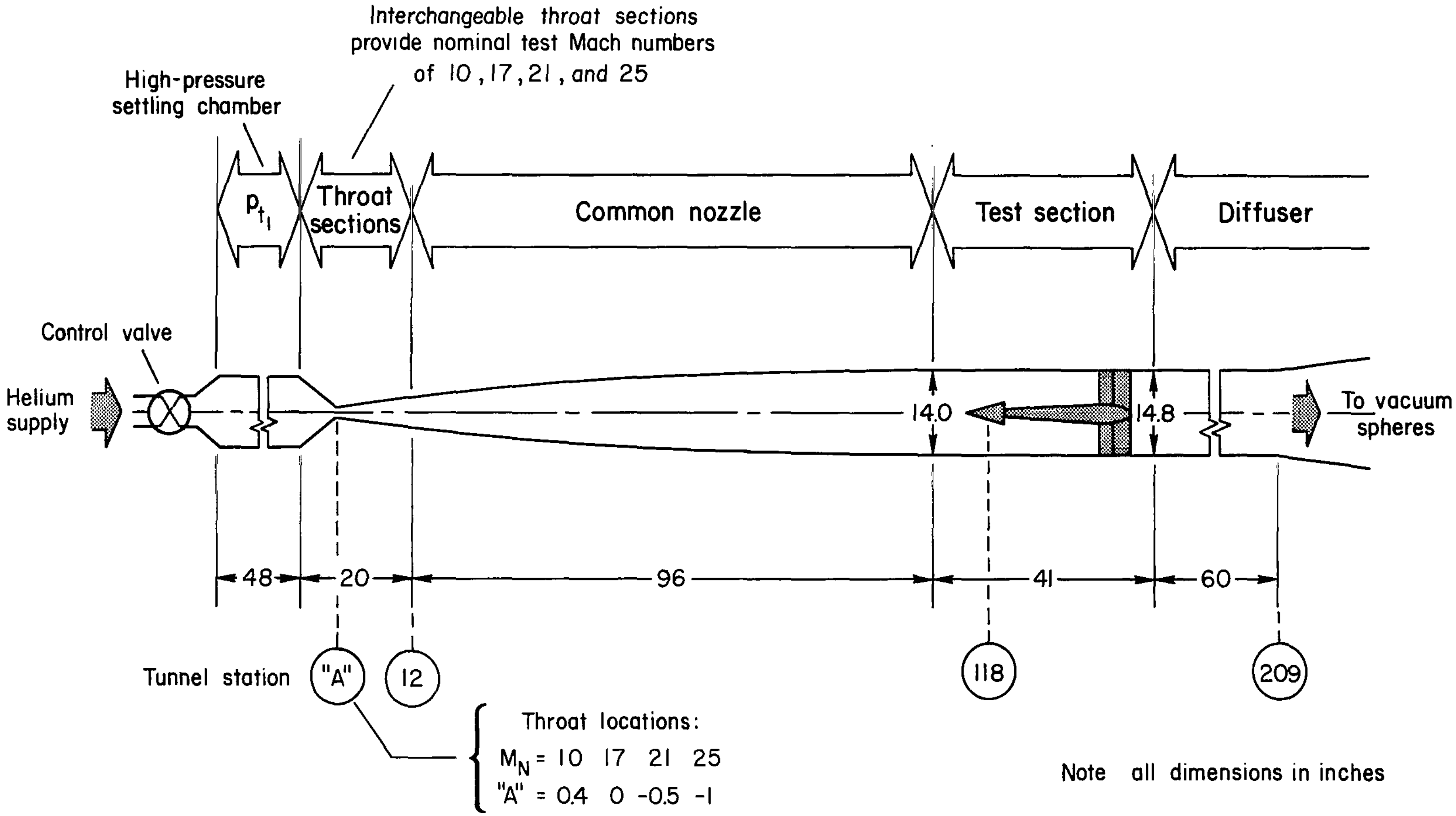

Figure 1.- Schematic diagram of the Ames 14-inch helium tunnel.

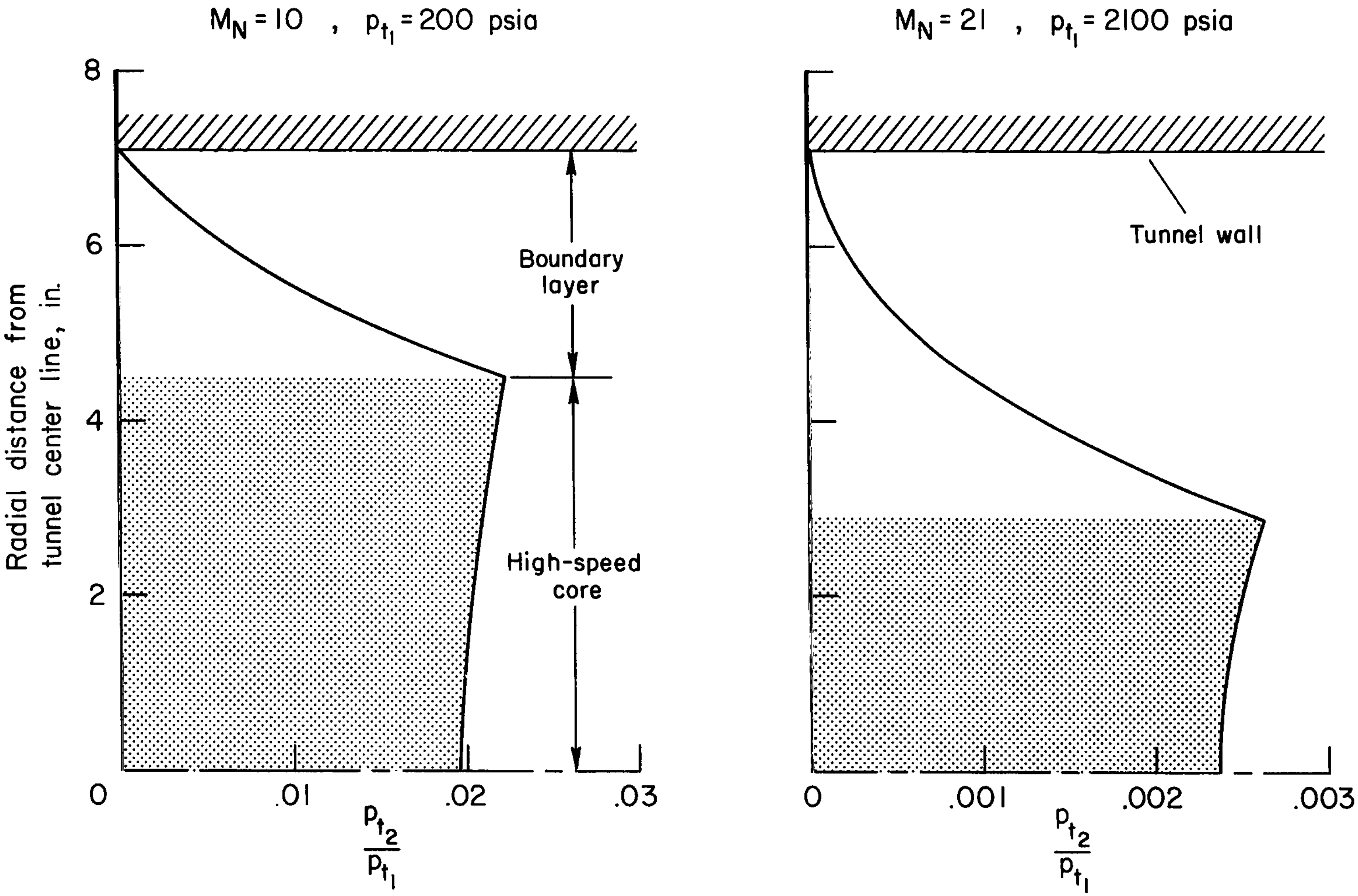

Figure 2.- Typical pitot-pressure surveys in the test section of the Ames 14-inch helium tunnel.

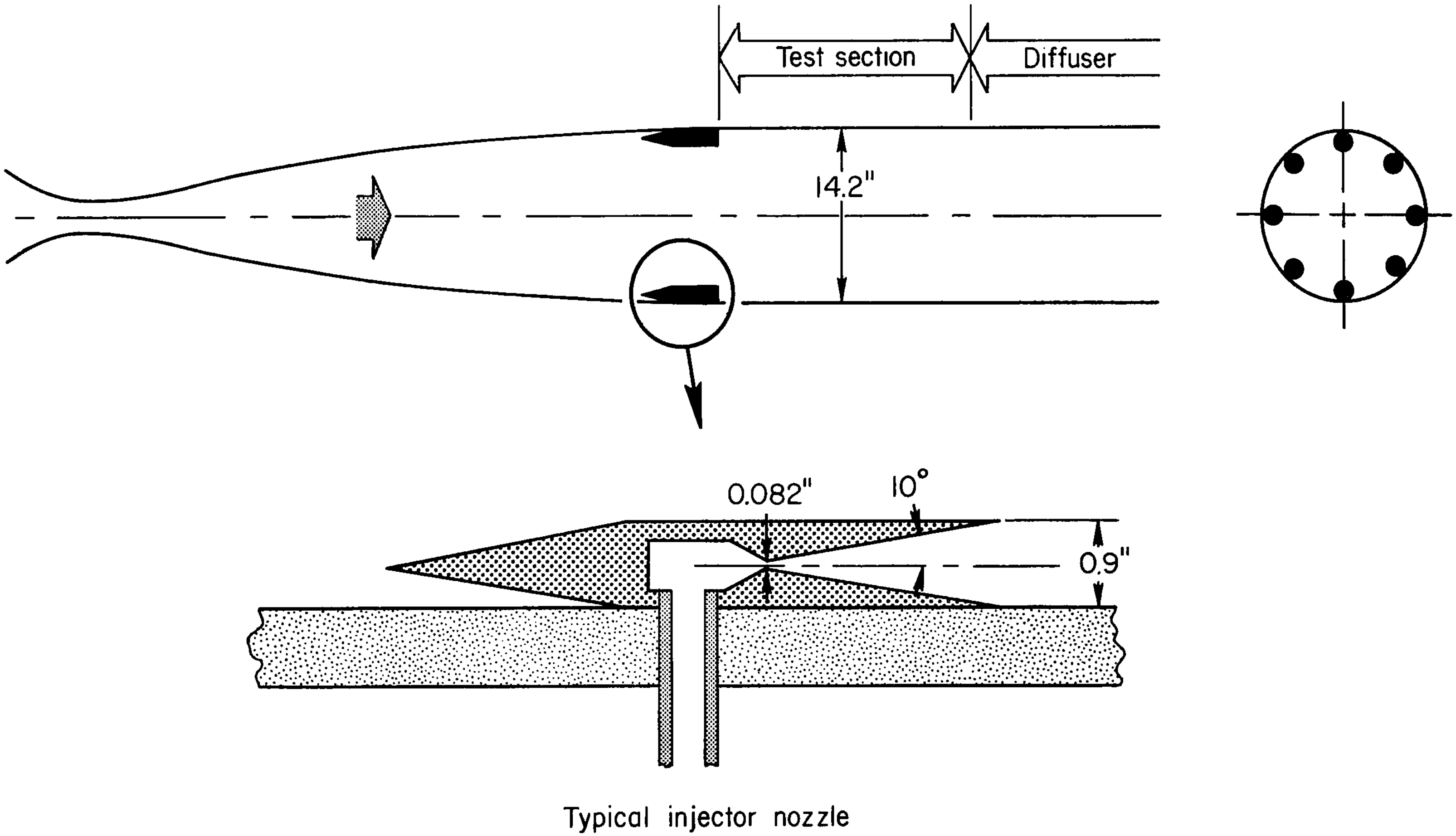

Figure 3.- Schematic diagram of discrete injector system.

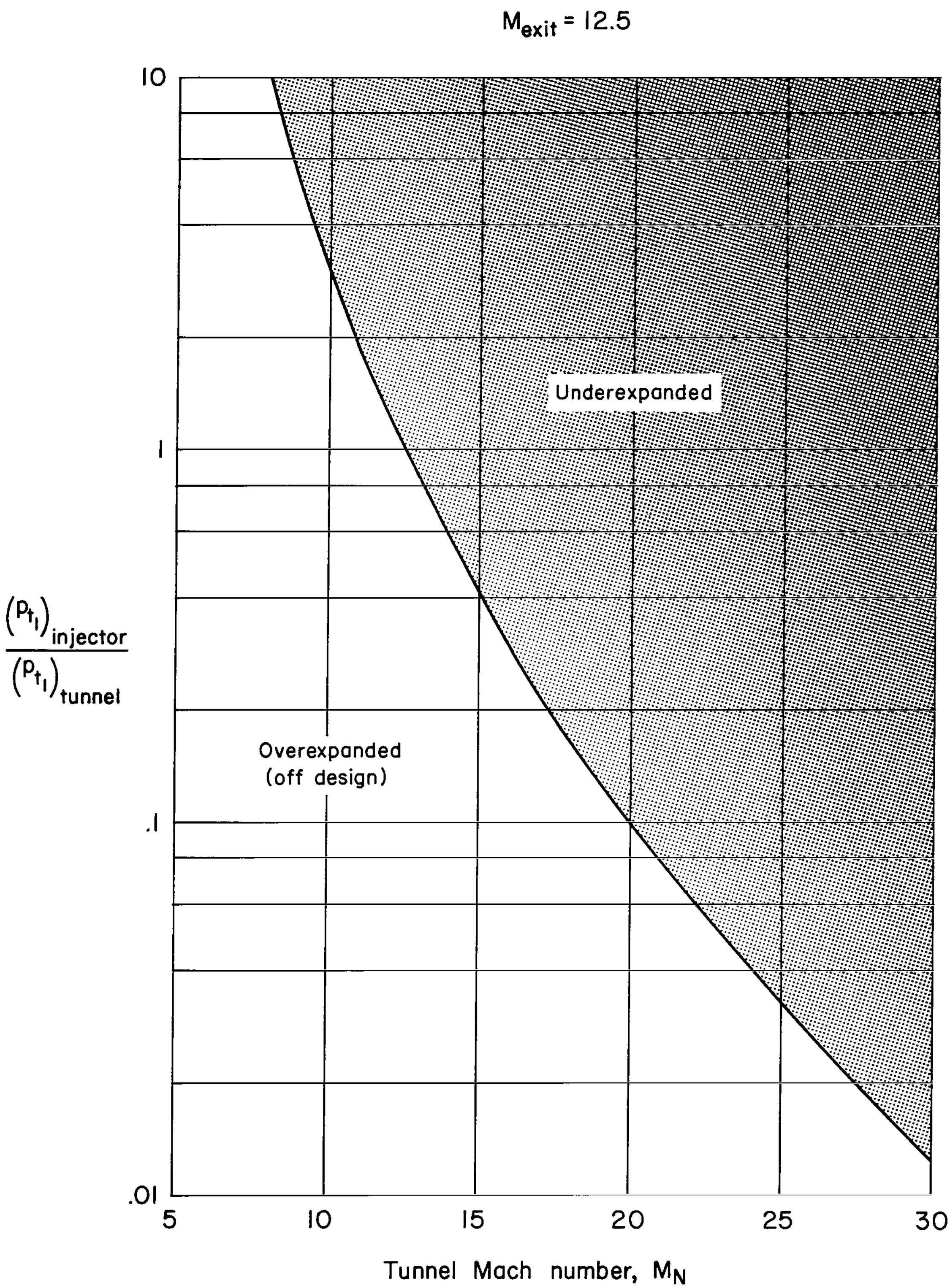

Figure 4.- Pressure requirement for operation of the injector nozzles in the "underexpanded" condition (injector exit design Mach number of 12.5).

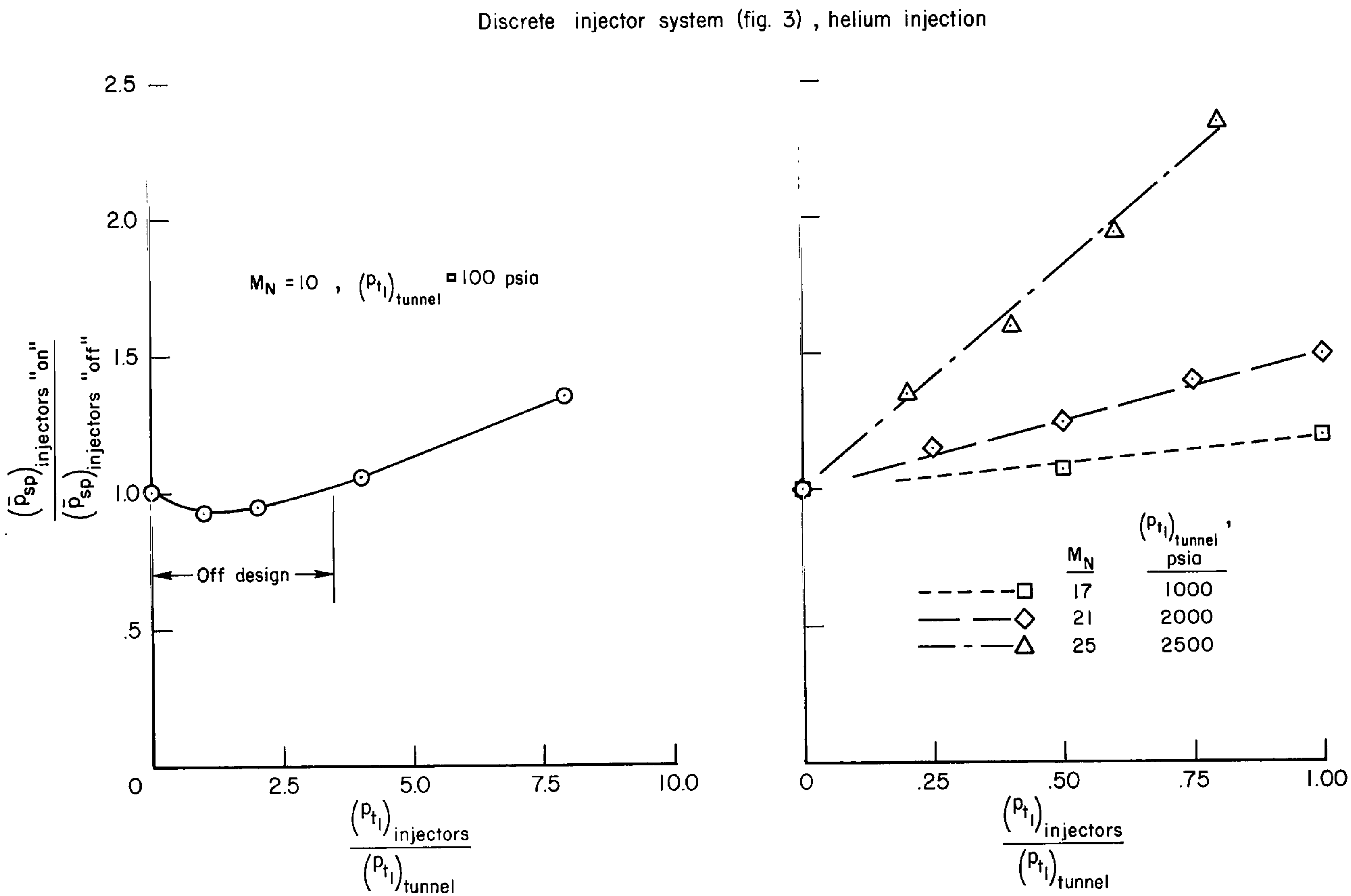

Figure 5.- Performance of discrete injector system with helium gas injection.

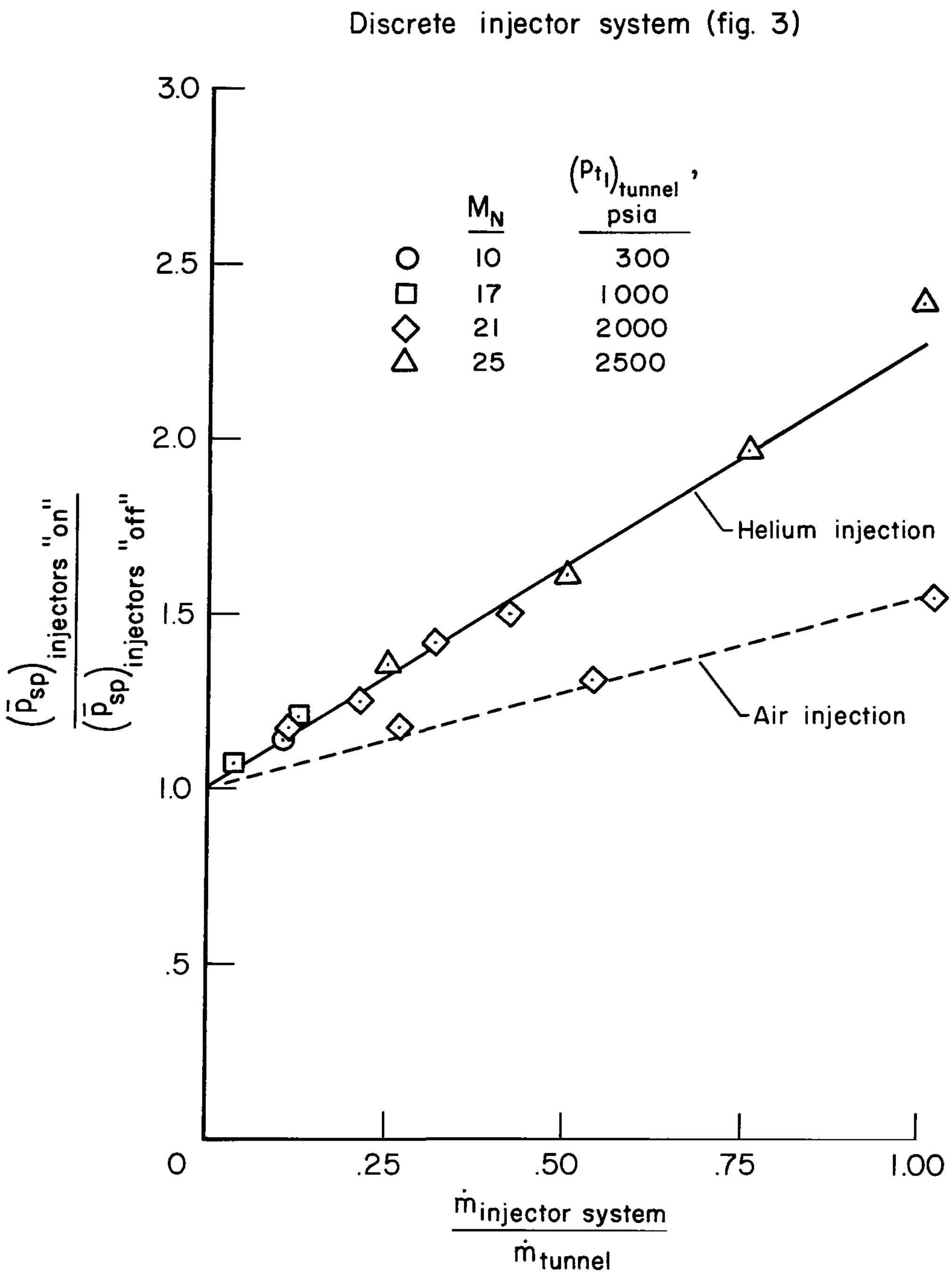

Figure 6.- Comparison of injector performance for helium and air injection.

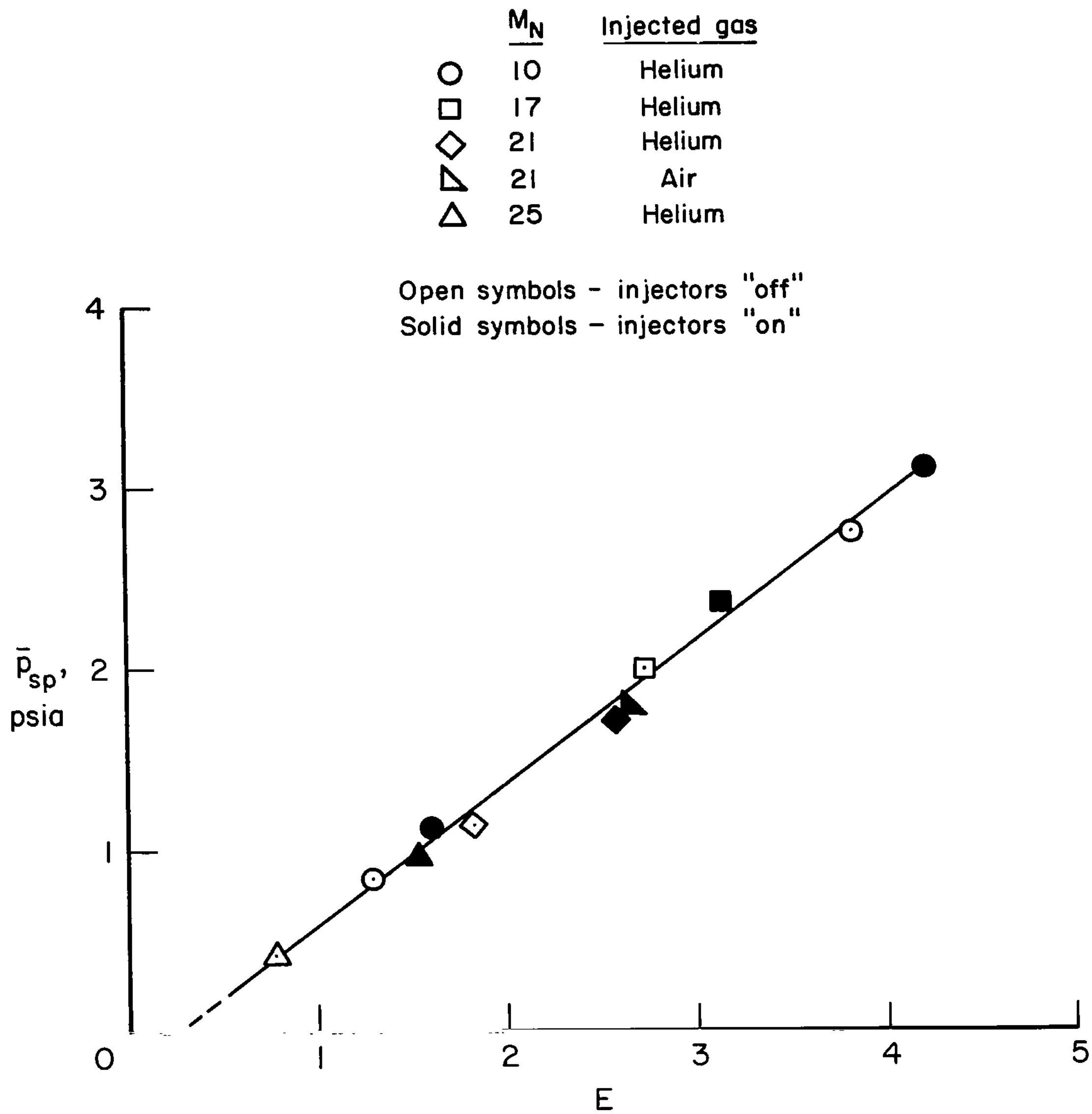

Figure 7.- Correlation of measured pressures in the downstream spheres at breakdown of the tunnel hypersonic flow with a stream energy parameter.

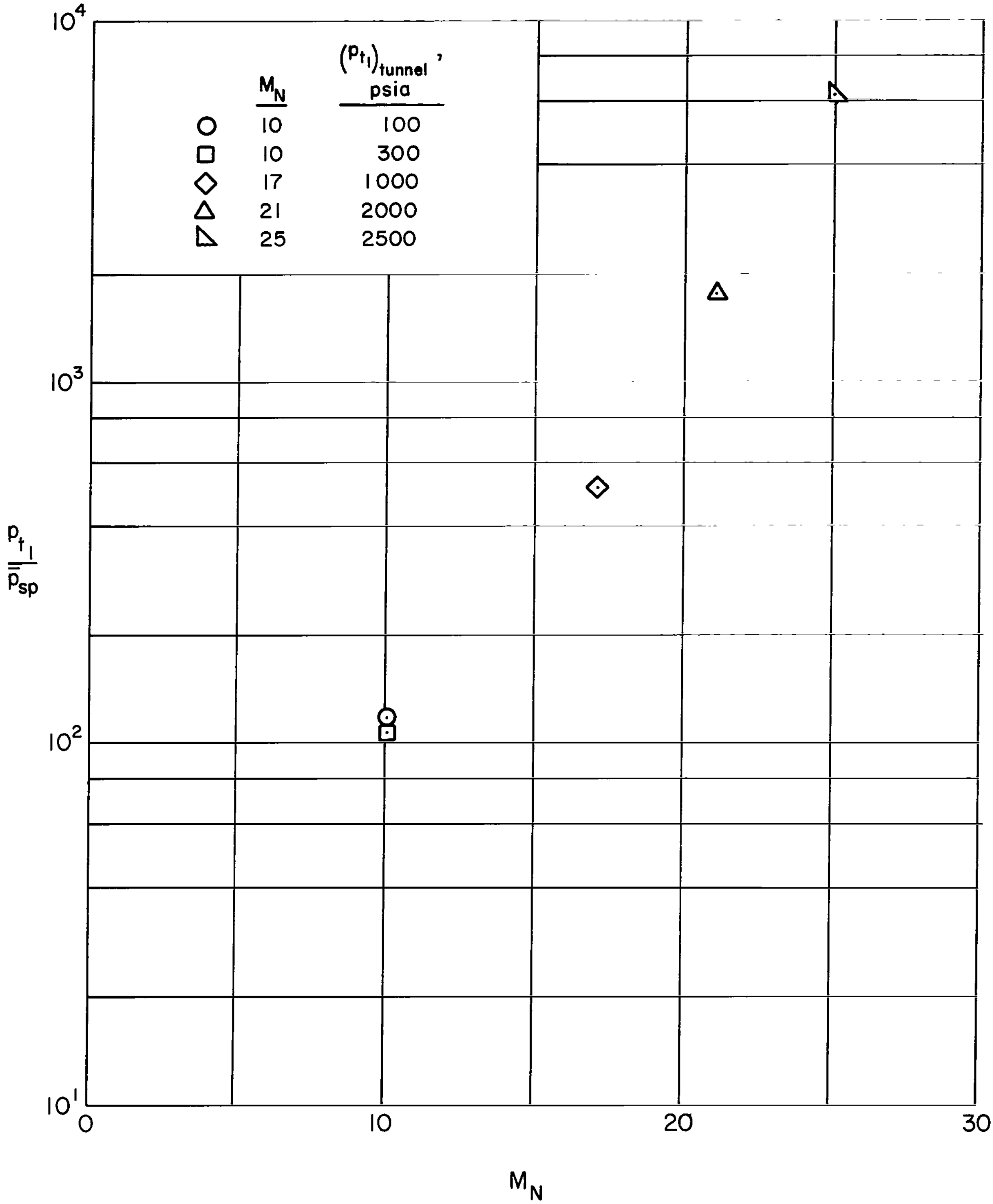

Figure 8.- Variation of tunnel compression ratio with Mach number (data from table I, $\dot{m}_{injectors} = 0$).

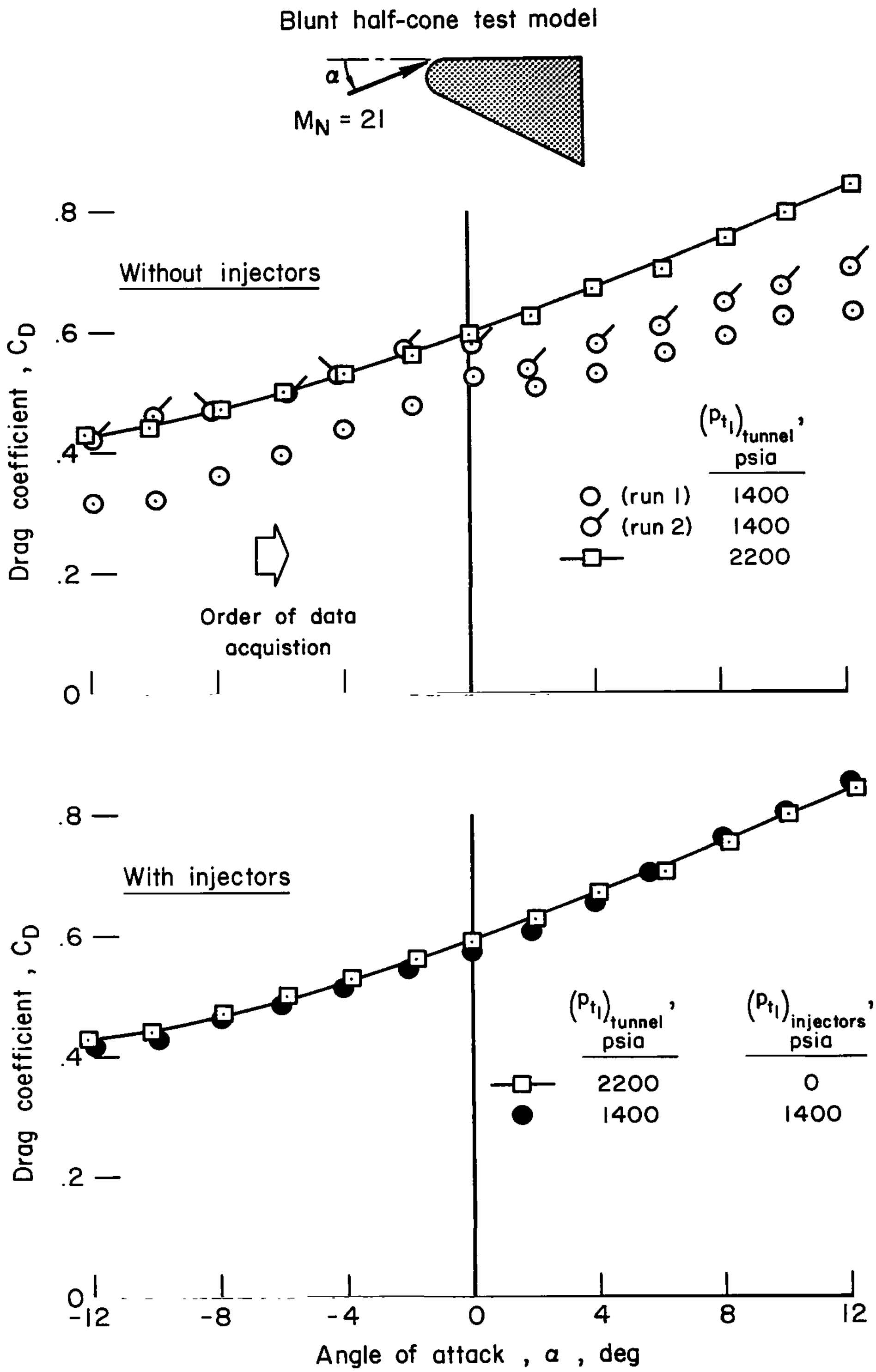

Figure 9.- Effectiveness of the injector system in eliminating the tunnel boundary-layer feedback problem.

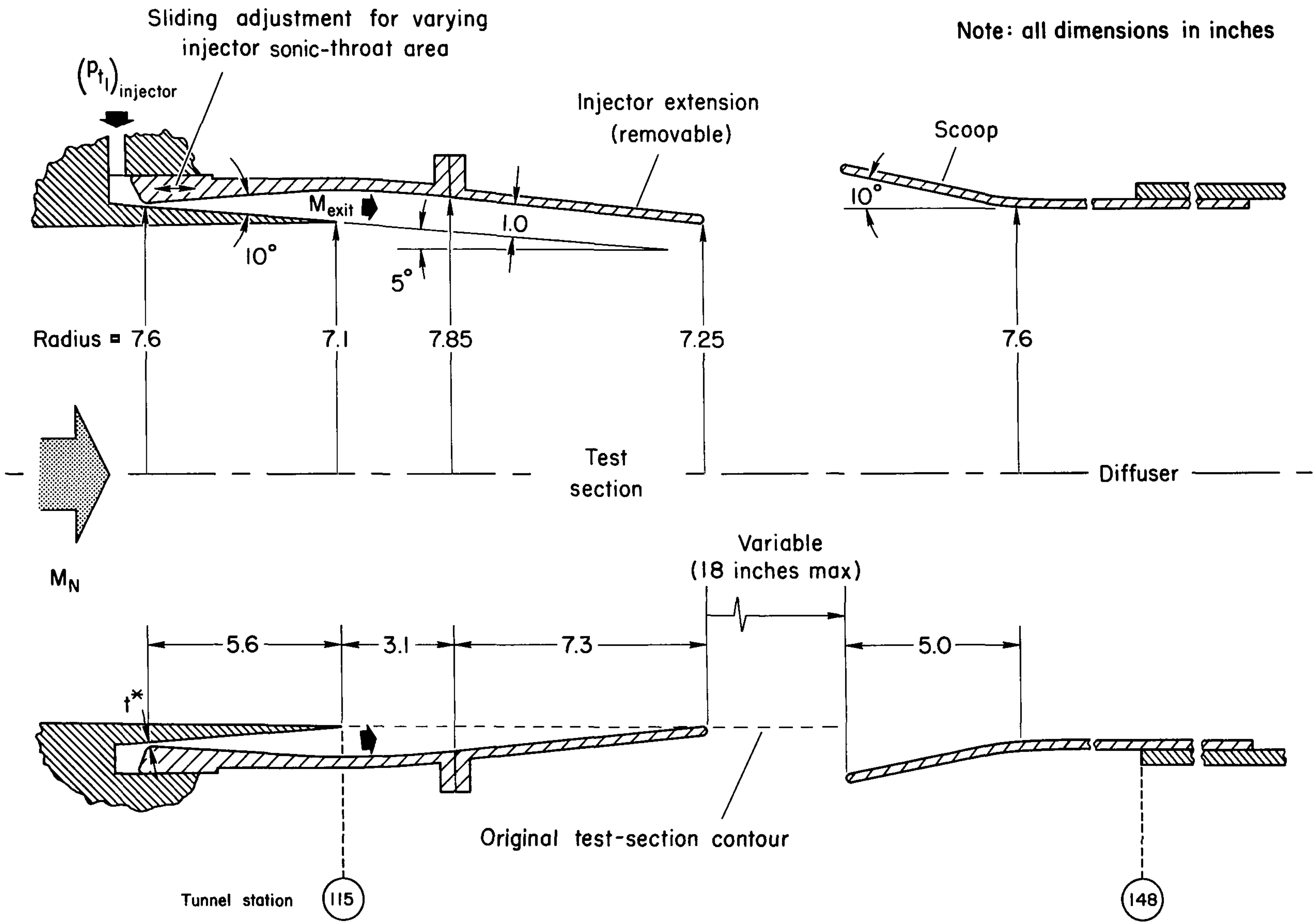

Figure 10.- Schematic diagram of annular injector.

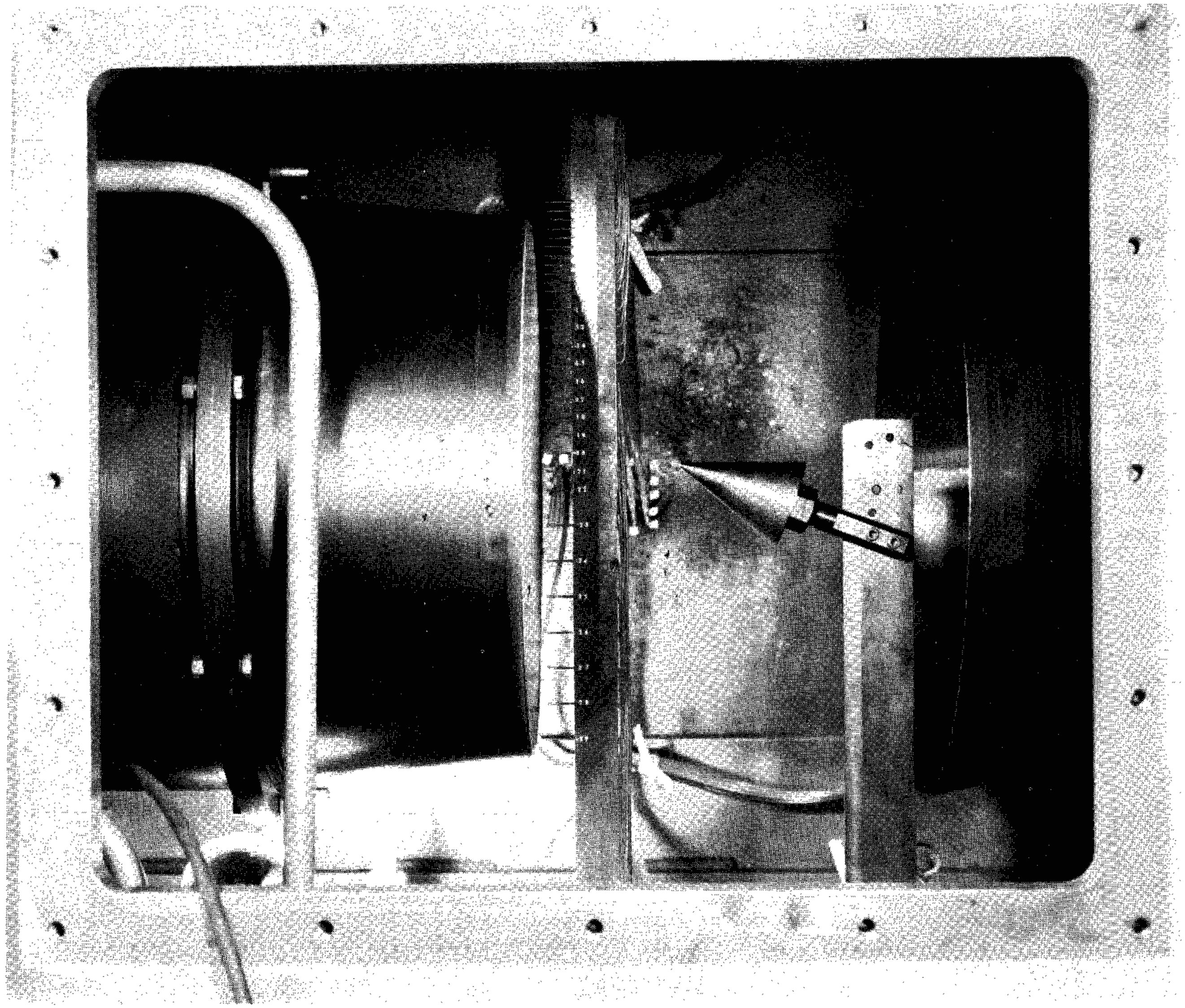

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Figure 11.- Photograph of annular gas injector with pitot rake and cone model installed at 20° angle of attack.

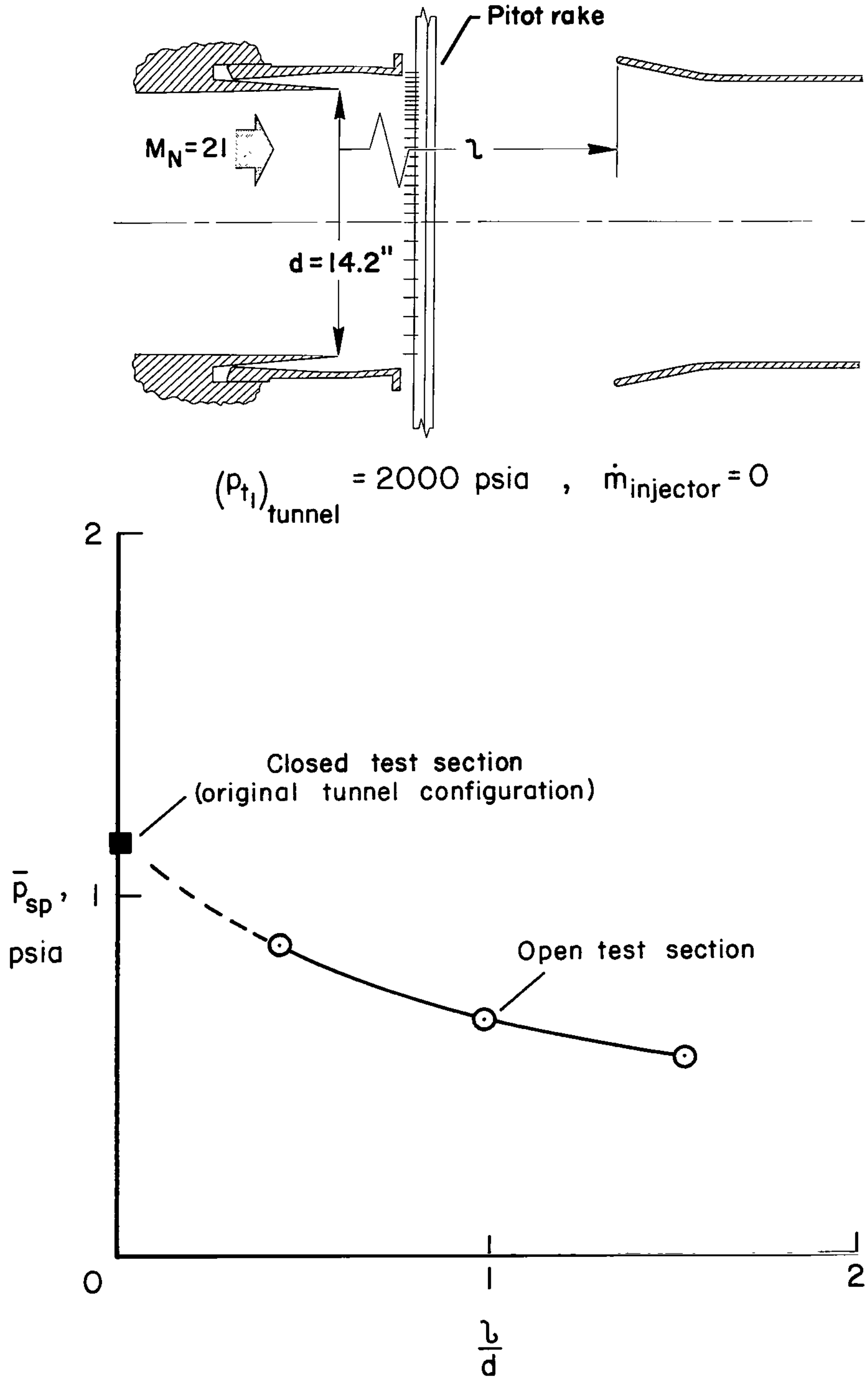

Figure 12.- Comparison of tunnel performance for closed and open test sections.

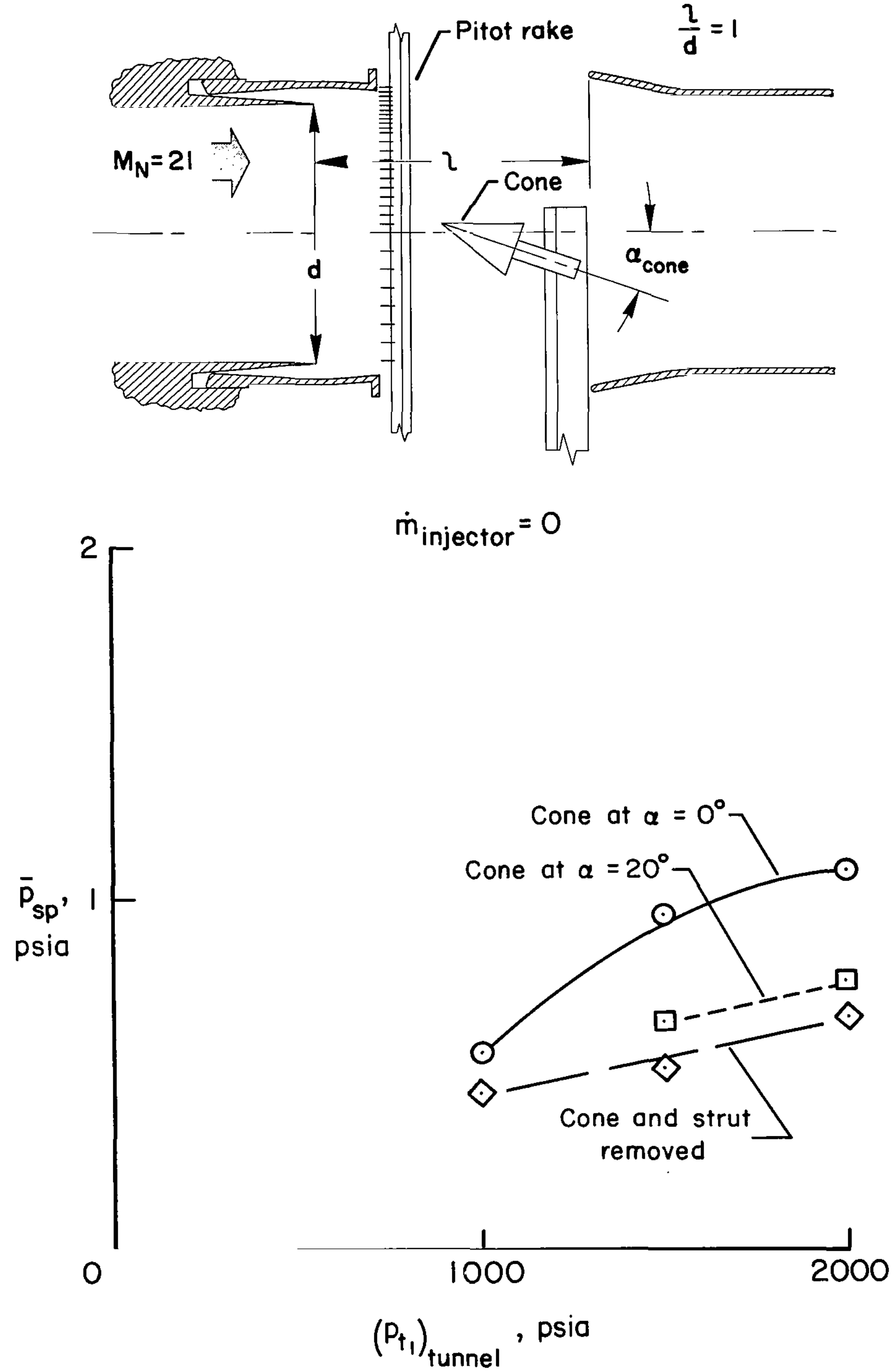

Figure 13.- Effect of cone model on tunnel performance.

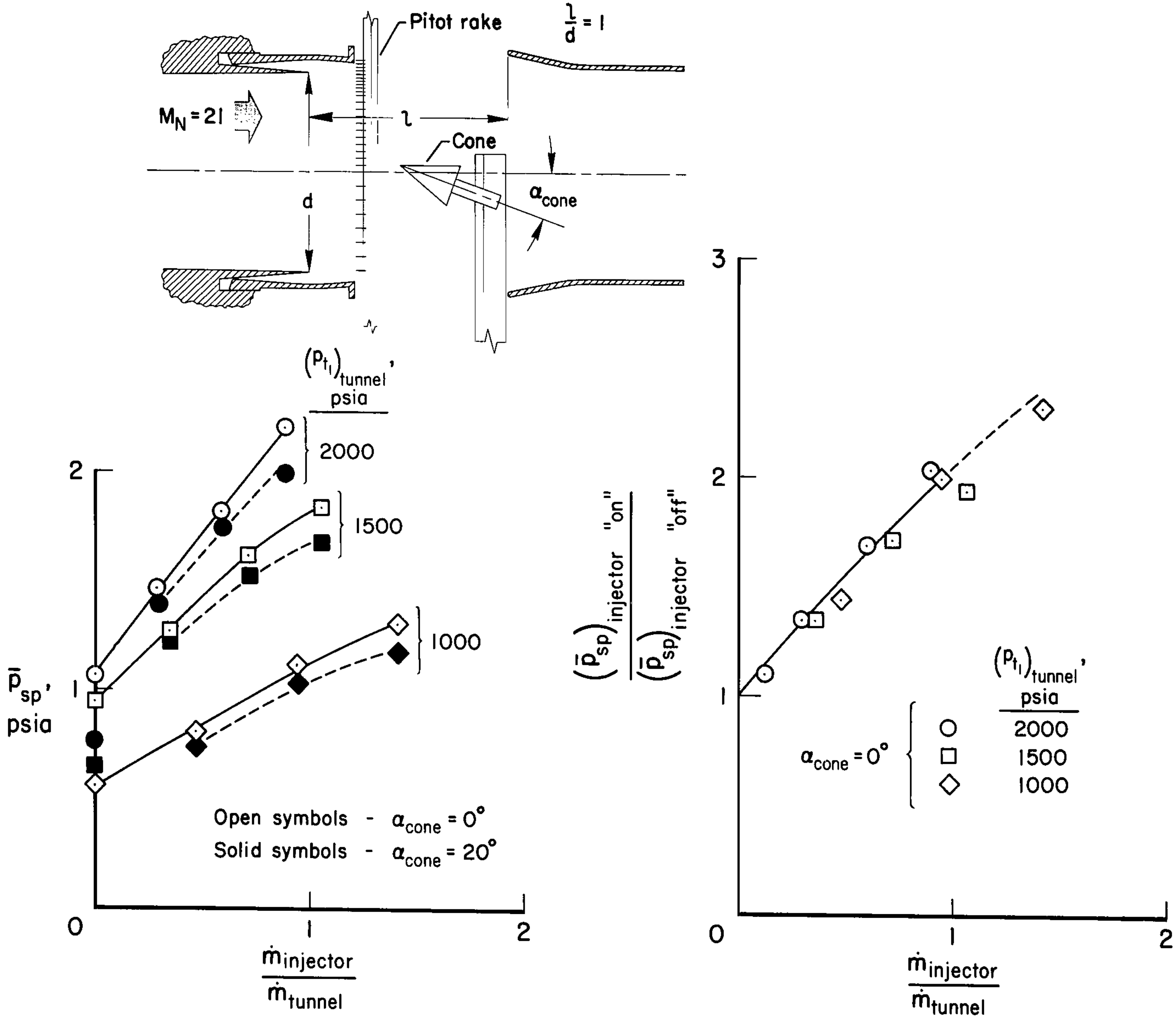

Figure 14.- Performance of annular injector; helium injection, $M_\infty = 21$.

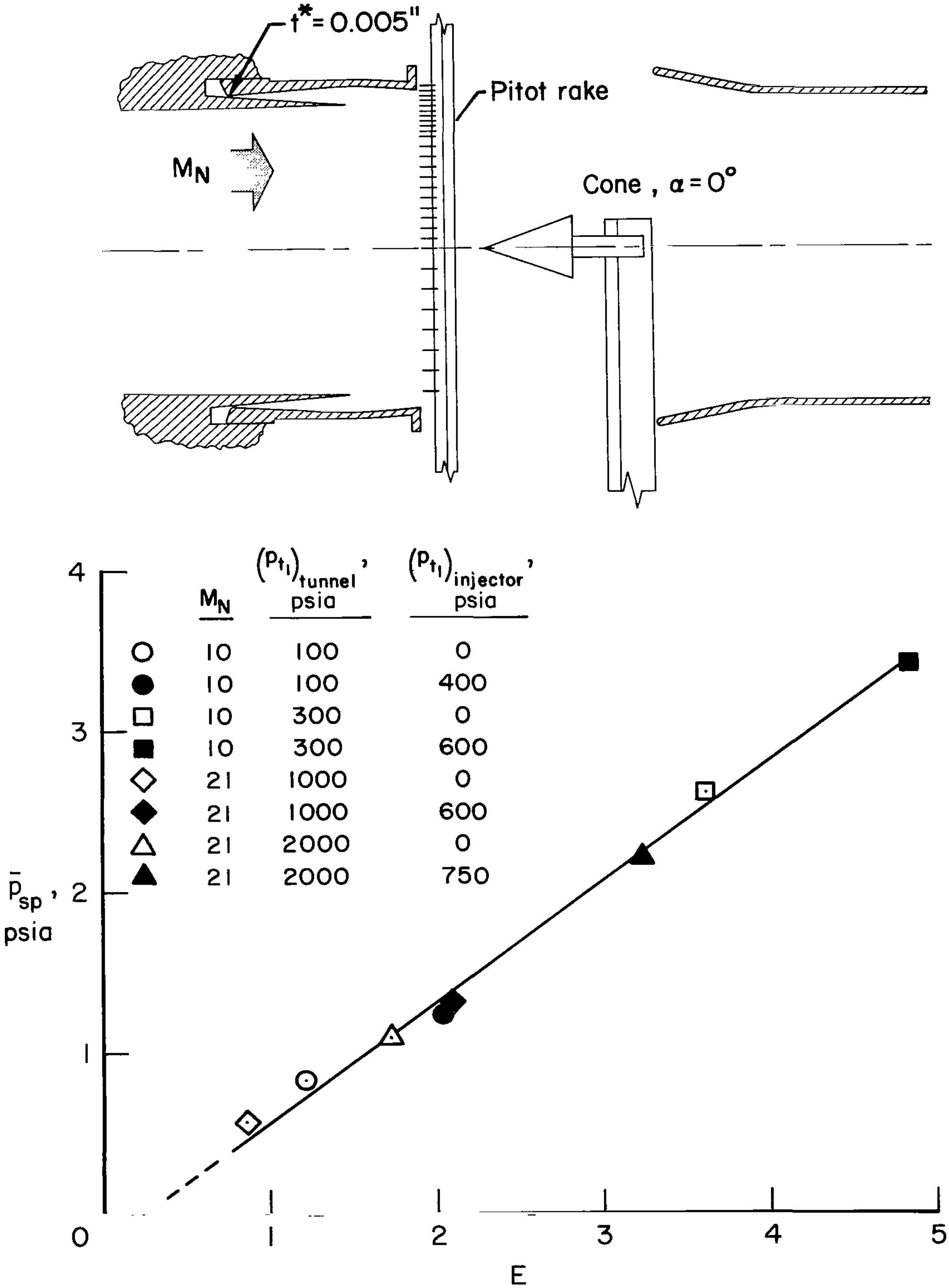

Figure 15.- Correlation of performance data for the annular injector system.

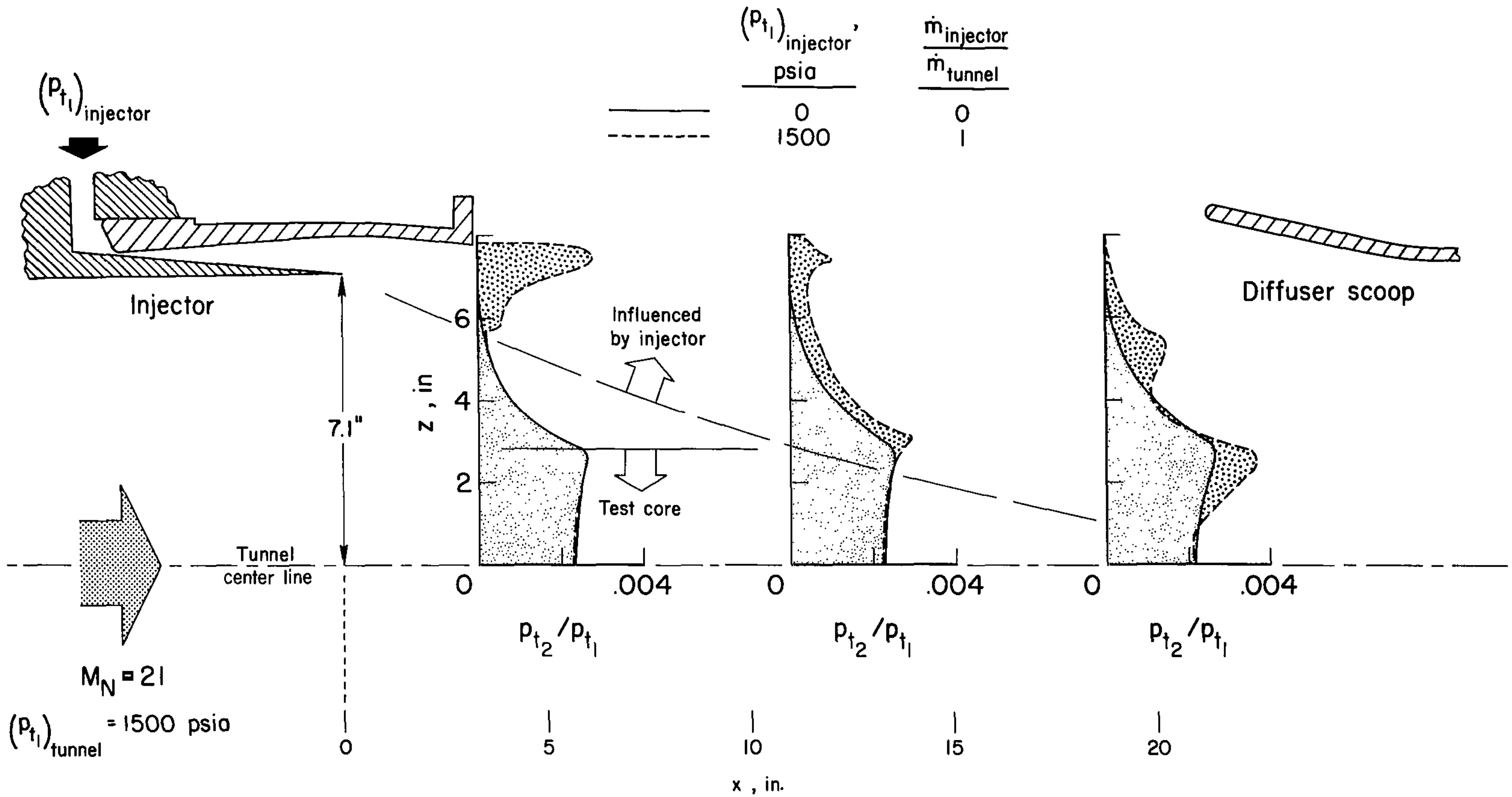

Figure 16.- Pitot-pressure surveys indicating the domain of influence of the injected gas.

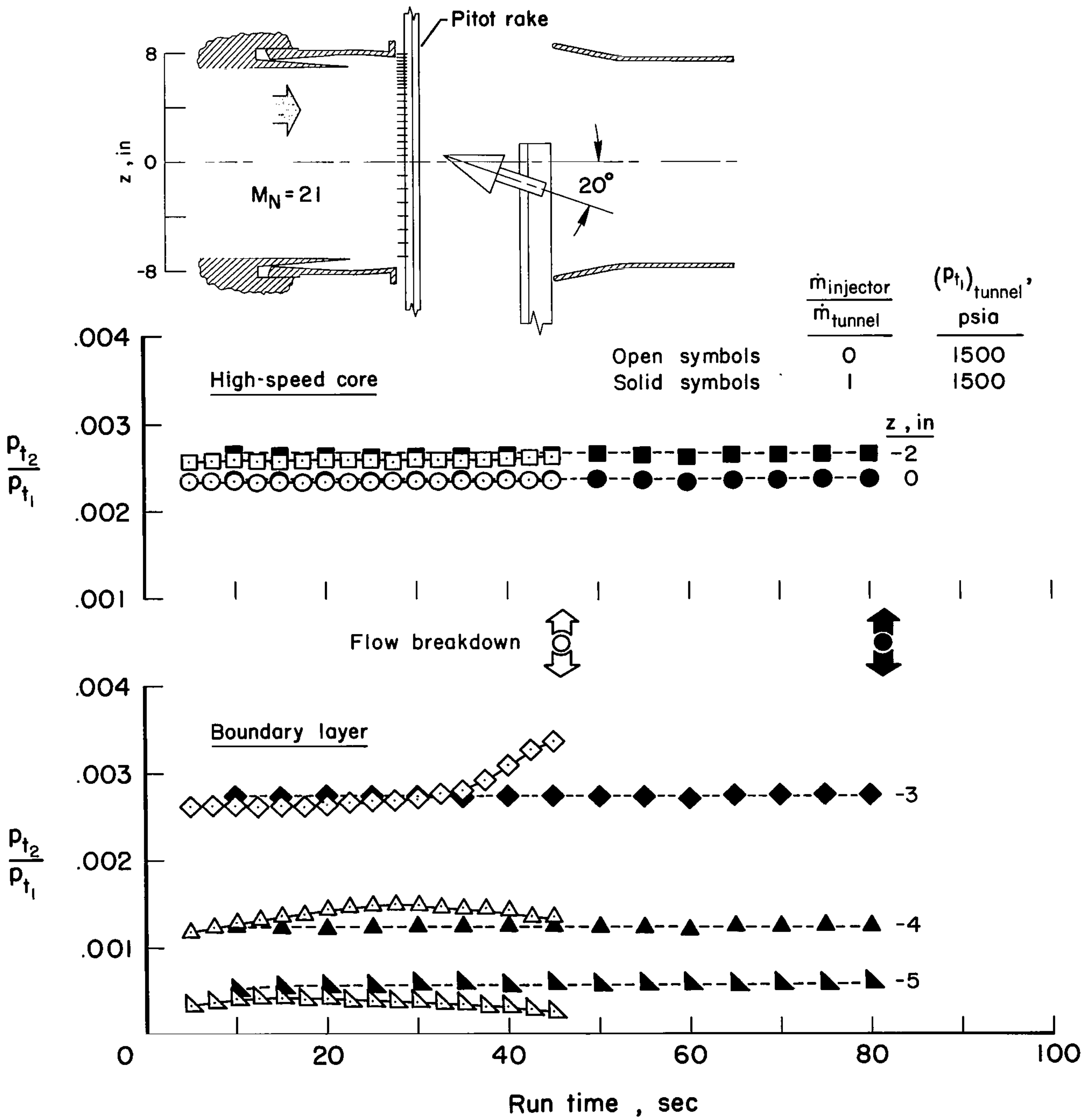

Figure 17.- Variation of tunnel-stream pitot pressure with time; with and without boundary-layer injection.

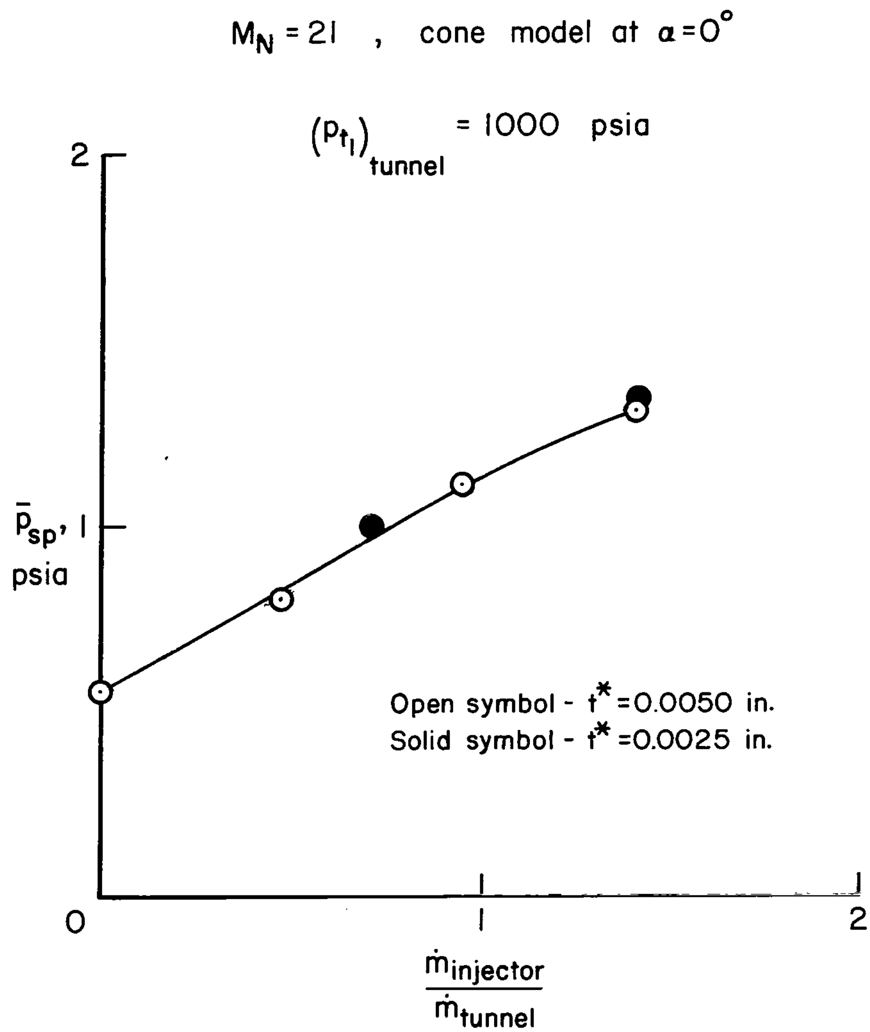

Figure 18.- Comparison of annular injector performance for two injector sonic-throat openings.

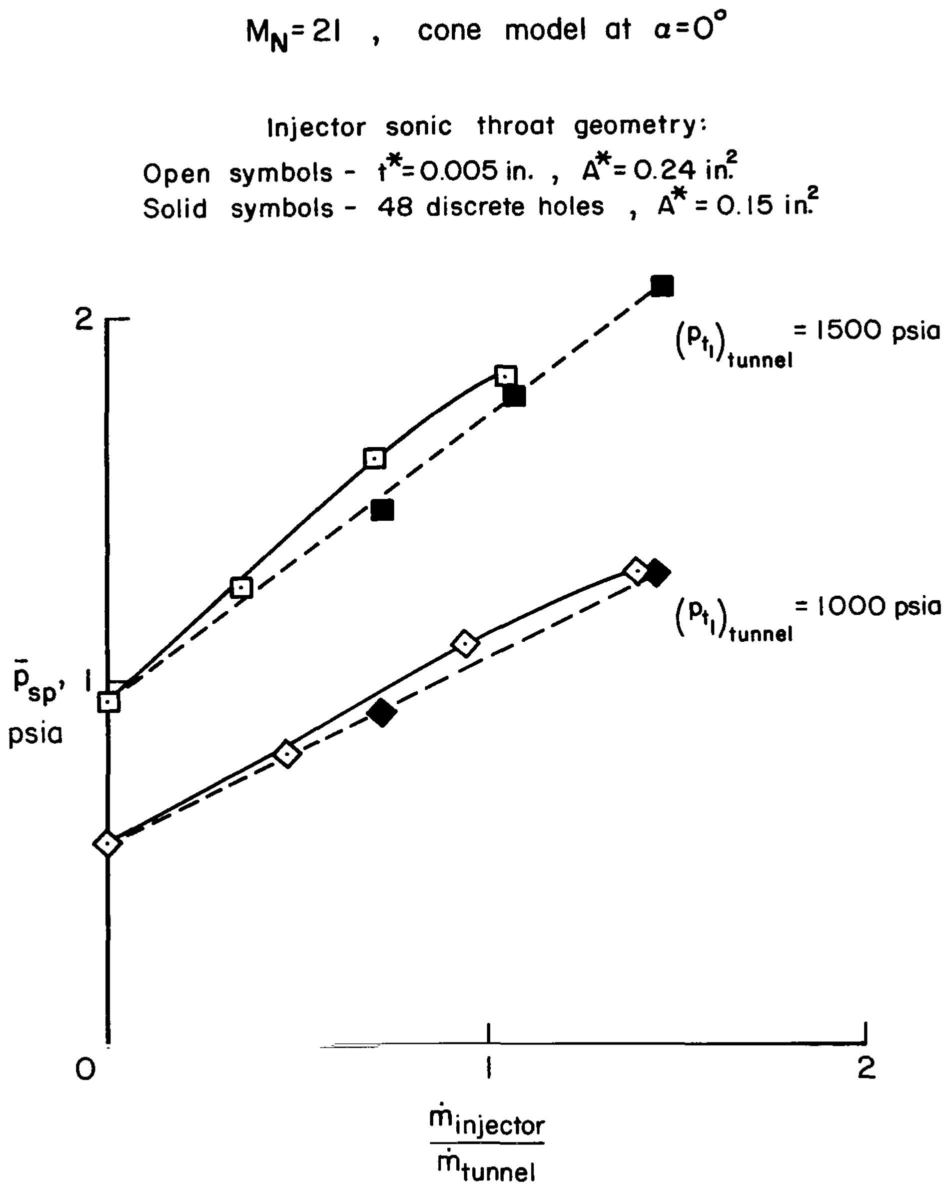

Figure 19.- Comparison of injector performance for an annular sonic throat and a sonic throat consisting of 48 discrete holes.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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